Modeling Directional Thermal Radiance from a Forest Canopy

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FOREWORD

SWOE Report 89-6, 1989, was prepared by M.J. McGuire of Department of Resources, University of New Hampshire, Durham, New Hampshire, Dr. L.K. Balick of EG&G Energy Measurements, Inc., Las Vegas, Nevada, Dr. J.A. Smith of Laboratory for Terrestrial Physics, Goddard Space Flight Center, Greenbelt, Maryland and B.A. Hutchison of Kingston, Tennessee.

This report is a contribution to the Smart Weapons Operability Enhancement (SWOE) Program. SWOE is a coordinated, Army, Navy, Marine Corps, Air Force and DARPA program initiated to enhance performance of future smart weapon systems through an integrated process of applying knowledge of the broadest possible range of battlefield conditions.

Performance of smart weapons can vary widely, depending on the environment in which the systems operate. Temporal and spatial dynamics significantly impact weapon performance. Testing of developmental weapon systems has been limited to a few selected combinations of targets and environment conditions, primarily because of the high costs of full-scale field tests and limited access to the areas or events for which performance data are required.

Performance predictions are needed for a broad range of background environmental conditions and targets. Meeting this need takes advantage of significant DoD investments by Army, Navy, Marine Corps and Air Force in 1) basic and applied environmental research, data collection, analysis, modeling and rendering capabilities, 2) extensive target measurement capabilities and geometry models, and 3) currently available computational capabilities. The SWOE program takes advantage of these DoD investments to produce an integrated process.

SWOE is developing, validating, and demonstrating the capability of this integrated process to handle complex target and background environment interactions for a world-wide range of battlefield conditions. SWOE is providing the DoD smart weapons and autonomous target recognition (ATR) communities with a validated capability to integrate measurement, information base, modeling and scene rendering techniques for complex environments. The result of a DoD-wide partnership, this effort works in concert with both advanced weapon system developers and major weapon system test and evaluation programs.

The SWOE program started in FY89 under Balanced Technology Initiative (BTI) sponsorship. Present sponsorship is by the U.S. Army Corps of Engineers (lead service), the individual services, and the Joint Test and Evaluation (JT&E) program of the Office of the Director of Defense Research and Engineering (DDR&E), Office of the Secretary of Defense (OSD).

The Program Director is Dr. L.E. Link, Technical Director of the U.S. Army, Cold Regions Research and Engineering Laboratory (CRREL). The Program Manager is Dr. J.P. Welsh, CRREL. The Integration Manager is Mr. Richard Palmer, CRREL. The task areas and their managers are as follows: Modeling Task Area, LTC George G. Koenig, USAF, Geophysics Laboratory (GL), of the Air Force Phillips Laboratories; Information Bases Task Area, Mr. Harold W. West, PE, U.S. Army Engineer, Waterways Experiment Station (WES); Scene Rendering Task Area, Mr. Mike Hardaway, Corps of Engineers, Topographic Engineering Center (TEC); Validation Task Area, Dr. Jon Martin, Atmospheric Sciences Laboratory (ASL) of the Army Materiel Command.

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Recent advances in remote sensing technology have increased interest in utilizing the thermal-infrared region to gain additional information about surface features such as vegetation canopies. Studies have shown that sensor view angle, canopy structure, and percentage of canopy coverage can affect the response of a thermal sensor. These studies have been primarily of agricultural regions and there have been relatively few examples describing the thermal characteristics of forested regions. This paper describes an extension of an existing thermal vegetation canopy radiance model which has been modified to partially account for the geometrically rough structure of a forest canopy. Fourier series expansion of a canopy height profile is used to calculate improved view factors which partially account for the directional variations in canopy thermal radiance transfers. The original and updated radiance model predictions are compared with experimental data obtained over a deciduous (oak–hickory) forest site. The experimental observations are also used to document azimuthal and nadir directional radiance variations. Maximum angular variations in measured canopy temperatures were 4–6°C (azimuth) and 2.5°C (nadir). Maximum angular variations in simulated temperatures using the modified rough surface model was 4°C. The rough surface model appeared to be sensitive to large gaps in the canopy height profile, which influenced the resultant predicted temperature.

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BACKGROUND ON THERMAL REMOTE SENSING

The last decade has seen significant advances in the use of remote sensing technology to infer various characteristics about the earth's resources. A major portion of these advances has dealt with the visible and near-infrared regions of the electromagnetic spectrum (between 0.4 and 2.5 μm). More recently, there has been an increased interest in utilizing the thermal-infrared region (especially the 8.0–14.0 μm region) to gain additional information about these resources (Kimes, 1980). Examples of recent remote sensing applications in the thermal region include agricultural/evapotranspiration (ET) studies, extracting miner-

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alogic information for geologic exploration (Kahle and Goetz, 1983; Goetz et al., 1983; Gillespie and Kahle, 1977), providing additional sources of information in multispectral classifications (Price, 1981) and in military research, target/background discrimination (Weiss, 1984).

The agricultural/ET applications that have been reported are either on the scale of individual crop fields or on larger, regional scales. Crop temperatures have been measured with infrared thermometers near the canopy surface (e.g., Heilman et al., 1981; Hatfield, 1979; Kimes, 1980; Kimes et al., 1980), and with airborne thermal scanners (e.g., Millard et al., 1978; Heilman et al., 1976). Regional scale ET studies have utilized airborne thermal scanners (Soer, 1980; Pierce and Congalton, 1988) and satellite thermal-infrared data (Price, 1982; Cheevasuvit et al., 1985). These studies have shown promising results for using remotely sensed temperature measurements for such things as determining water status of vegetation canopies, crop yields, and soil moisture conditions. However, there are relatively few examples where this technology has been applied specifically to forested regions (e.g., Rhode and Olson, 1970; Bonn, 1977; Balick and Wilson, 1980; Fritschen et al., 1982; Balick and Hutchison, 1986; Sader, 1986; Pierce and Congalton, 1988).

The increasing interest in the thermal region is also evidenced by the various imaging systems that have been developed over the years. In a recent survey by Slater (1985), of the 56 imaging systems described, about 20 systems have been developed or are proposed which contain a channel for the thermal region. To make the most efficient use of the information obtained by these thermal imaging systems, it is very important to relate the remotely sensed data to the underlying scene phenomenon (Kimes et al., 1981). Mathematical modeling can be used to study the complex energy interactions which take place within the underlying scene and to help understand and differentiate between various surface features (Kimes, 1979).

THERMAL VEGETATION CANOPY MODELS

A model that can be used to study the energy flows within a vegetation canopy is discussed by Smith et al. (1981). This thermal vegetation canopy model (TVCM) is a modification of an earlier model reported by Kimes (1979) and Kimes et al. (1981) which is a physically based model that predicts sensor response to thermal exitance from vegetation canopies. The model takes into account the canopy architecture when computing the radiant transfer of energy within and above the canopy, and also predicts the response of a thermal sensor above the canopy as a function of nadir view angle (Kimes et al., 1981). Other thermal models are available which incorporate vegetation characteristics with varying degrees of complexity (e.g., Choudhury and Idso, 1984; Smith, 1983; Balick et al., 1981; Welles et al., 1979; Deardoff, 1978; Sutherland and Bartholic, 1977).

Advances in thermal sensor technology have made it desirable to model the full angular variations in thermal response as well as the increased complexity of the surface features that can be described. Recent studies have shown that sensor view angle, canopy structure, and percentage of canopy coverage can effect the response of a thermal sensor (Hatfield, 1979; Jackson et al., 1979; Kimes, 1980; Kimes et al., 1980; Heilman et al., 1981; Kimes, 1983; Hatfield et al., 1984; Dozier and Warren, 1982; Sader, 1986; Pierce and Congalton, 1988).

Many thermal scanner missions have been traditionally flown at night to avoid the problems of differential heating and shadowing due to solar radiation and topography (Sabins, 1973). For vegetation modeling studies such as ET or water stress research, the optimum time for thermal measurements is at the time of maximum solar heating, i.e., 1–2 h past solar noon (Rhode and Olson, 1970; Millard et al., 1978). Thus, if this new technology is to be extended to evaluating a forest canopy, e.g., ET studies, the daytime differential heating needs to be better understood. Modeling the full range of sensor viewing angles, as well as accounting for increased scene complexity, would add to the understanding of the thermal responses from a forest canopy.

OBJECTIVES

The TVCM as presented by Smith et al. (1981) has two shortcomings with regard to these new prediction demands. These are the lack of azimuth view

angle thermal radiance prediction capabilities and the one-dimensional terrain element complexity limitations. This paper is intended to address these two issues. Specifically, the basic objectives are:

1. To document the view angle variations in the thermal radiance from a forest canopy (nadir and azimuth angles) and evaluate the relative significance of these variations.
2. To evaluate a modification of the TVCM which attempts to partially account for the effects of the geometrically rough surface of a forest canopy upon the thermal radiance distribution.

Thermal radiance from a forest canopy was evaluated theoretically and measured at various viewing angles. Simulated canopy temperatures are then compared with the field measurements. The variations with view angle are used to investigate how azimuthal prediction capabilities may be included in the TVCM. Introducing the geometrically rough surface layer sets the stage for expanding the model to include three-dimensional scenes (e.g., Kimes and Kirchner, 1982; Cooper and Smith, 1985).

THE ORIGINAL THERMAL MODEL—ORIG

The original thermal modeling work initiated by Kimes (1979) and Kimes et al. (1981) is based on a mathematical abstraction of three horizontal layers of vegetation. Additional sources of thermal energy are included for the sky and underlying ground layers. An energy budget equation was formulated for each vegetation layer and the roots of the resulting system of equations were taken to be the average temperature in the respective layers. Canopy geometry was taken into account by utilizing the leaf angle frequency distributions of the elements in a layer.

The model was subsequently modified by Smith et al. (1981) to a more tractable form, which permitted target/background studies to be performed more efficiently. The updated model had three major modifications. A significant one was the state-space characterization of the energy budget equations and factorization of the long-wave energy terms into a geometric-dependent term (the S matrix) and an energy related term. This permitted the precalculation of the S matrix for a wide variety of canopies based on their geometric properties, which could then be coupled with the appropriate meteorological data to simulate various scenarios.

Another modification involved the numerical technique used to solve the system of nonlinear equations. An iterative Newton–Raphson technique (Burden et al., 1981) was used to improve the computational efficiency of the simulation model.

The third major change involved simplifying assumptions concerning the short-wave absorption coefficients estimated by a separate multiple scattering Monte Carlo model, the solar radiation vegetation canopy model (SRVC) (Kimes and Smith, 1980). In the Monte Carlo analyses, the authors found that the short-wave absorption coefficients varied as a function of solar zenith angle. However, for the thermal model, they assumed an average absorption coefficient value for each canopy layer.

Incorporating these modifications into the model, the matrix expression for the energy balance equations was

$$F = \tfrac{1}{2}\alpha\sigma B(X)^T S - \sigma B(X) + A + H(X) + LE(X) = 0, \quad (1)$$

where

X = average layer temperature vector for the three vegetation layers,

α = vector of long-wave absorptivity terms,

σ = Stefan–Boltzmann constant,

B = vector of long-wave emission terms,

A = vector of short-wave absorption terms,

H = vector of sensible heat,

LE = vector of evapotranspiration terms.

Standard expressions from the literature were utilized in the formulation of each energy budget component and are described in detail by the authors (Smith et al., 1981).

The modified model was evaluated with data collected from two diverse forest types, a coniferous forest (Douglas-fir; *Pseudotsuga Menziesii*) in Washington state and a deciduous forest (oak–hickory; *Quercus-Carya*) near Oak Ridge,

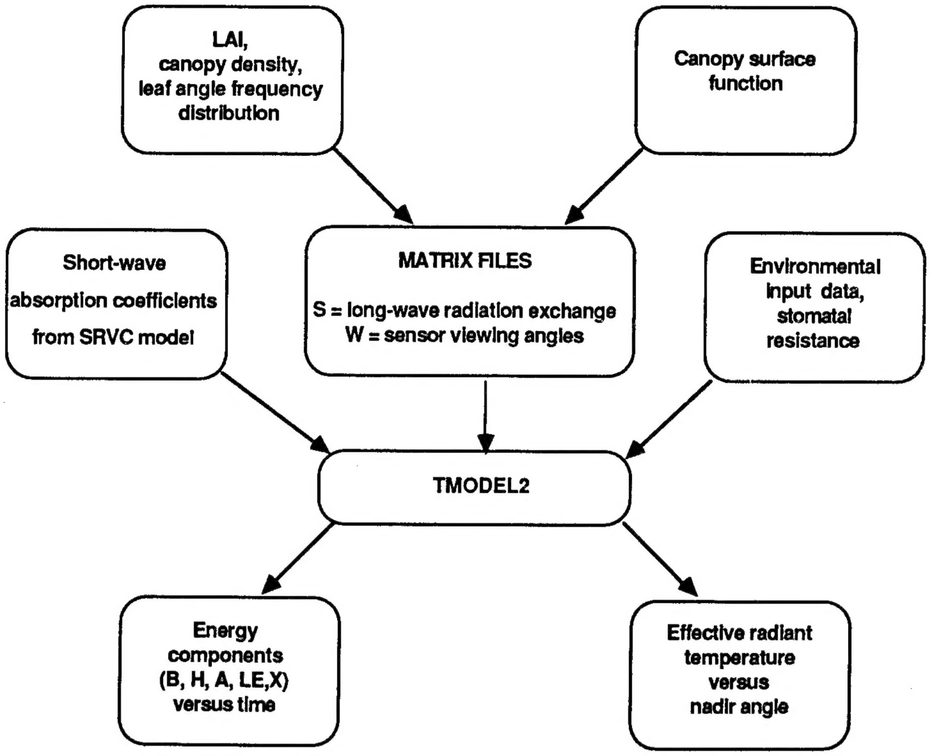


Figure 1. Original (ORIG) and rough surface thermal model (ROUGH) summary.

Tennessee. Comparison of the simulated and measured temperatures indicated that the model results were within 2°C of measured temperatures for both canopies.

The model formulated as Eq. (1) will be designated the original model (ORIG). The assumptions, input requirements, and outputs for ORIG are summarized briefly below.

1. The vegetation canopy is made up of three horizontal layers.
2. The model assumes a steady-state condition.
3. Energy fluxes due to photosynthesis, respiration, and heat storage in the soil and tree trunks are assumed negligible and are ignored.
4. Reflection of thermal flux within the canopy is ignored.
5. Individual canopy elements are assumed to emit thermal radiation in an isotropic manner.
6. An average short-wave absorption coefficient is used for each of the three vegetation layers.
7. Stomatal resistance may be an important consideration in the energy budget but it is a difficult parameter to measure; therefore, at this stage of the model's development a constant stomatal resistance value is used.

The inputs and basic structure of the ORIG and modified rough surface (ROUGH) models are summarized in Fig. 1. The modifications made in the ROUGH model primarily involve the canopy surface function which will be discussed later. The program first computes the canopy geometry dependent long-wave radiation exchange matrix (S) and the sensor view factor matrix (W). The required inputs include:

1. The leaf angle frequency distribution for each layer and inclination angle.
2. The leaf area index (LAI) for each layer.
3. The canopy density parameter, which is an index of the spatial dispersion of elements in the canopy, ranging from 0 to 1.

The S and W matrices are then coupled with the corresponding environmental input data, the short-wave absorption coefficients as determined by SRVC, and an average stomatal resistance value. The number of simulation runs is also input to correspond to the frequency of the meteorological data. These parameters make up the input to the thermal model (Program TMODEL2). The output files which are generated include the various energy components versus time and effective radiant

temperature (ERT) versus nadir view angle predictions.

ROUGH SURFACE MODEL—ROUGH

The model described above does not include azimuth view angle prediction capability, and is restricted to one-dimensional surfaces. One approach to provide these capabilities is suggested by the work of Welles et al. (1979) and Norman and Welles (1983). The idea is basically to weight the transfer of energy through a canopy by the relative distance a ray travels through the canopy at various nadir and azimuth angles. This travel distance distribution, coupled with a surface function to describe the undulating forest canopy, is taken to be the angular variation in canopy radiance. Including the surface function introduces the potential for incorporating two- and possibly three-dimensional effects into the thermal predictions. The modifications of the ORIG thermal model incorporating the above concepts required a reformulation of the probability of gap (P_{gap}) expression in the model and the development of new geometrical accounting routines. Li and Strahler (1988) and Nilson (1970) describe and compare several methods for modeling P_{gap}.

In the ORIG model, P_{gap} is used in the calculation of the S and W matrices to compute the canopy geometric-dependent radiation transfers and view factors. This treatment accounts for the "micro" geometric effects of the canopy on energy transfers within the canopy. Vegetation also exhibits a "macro" geometric structure when the canopy is taken as a whole (e.g., row and clumping effects). This "macro" structure gives rise to rough surface thermal effects.

The effects of rough surfaces on the transfer of radiation has been investigated by others in the optical regime (Cooper and Smith, 1985; Hapke, 1984; Otterman, 1984), in the thermal regime (Mahrer, 1982; Weiss, 1982; Kimes, 1981a,b; Jackson et al., 1979), and in the microwave region (Ulaby et al., 1982). Geometric solids, such as cones, cylinders, and ellipsoids have been used to approximate the shapes of trees (e.g., Li and Strahler, 1985; Strahler et al., 1984).

The original thermal model (ORIG) used the following expression for the probability of gap in a canopy layer (i), in direction θ:

$$P_{gap}(i,\theta) = \exp(-\mathrm{LAI}\,K/\cos\theta), \qquad (2)$$

where

$\mathrm{LAI} =$ leaf area index for the layer = one-sided leaf area per unit ground area,

$K = g(i,\theta) =$ mean canopy projection in direction θ,

$\theta =$ nadir angle.

This expression is then used in the computation of the original S matrix and W matrix (see Fig. 1).

Welles et al. (1979) and Normal and Welles (1983) present the following expression for the probability of gap, which takes into account path length variations with the nadir angle (θ) and the azimuth angle (ϕ):

$$P_{gap}(\theta,\phi) = \exp[-K\rho_f D(\theta,\phi)], \qquad (3)$$

where

$K =$ same as above,

$\rho_f =$ foliage density,

$D(\theta,\phi) =$ accumulated distance through the canopy at angle θ,ϕ.

After Norman and Welles (1983), we made the following assumptions and modifications.

The $\mathrm{LAI}/\cos\theta$ term in the original equation may be written as the product of ρ_f and $D(\theta,\phi)$:

$$\mathrm{LAI}/\cos\theta = \rho_f D(\theta,\phi). \qquad (4)$$

The foliage density ρ_f is defined as the foliage area per unit volume containing foliage:

$$\rho_f = L_a/L_v = L_a/G_a h = \mathrm{LAI}/h, \qquad (5)$$

where

$\rho_f =$ foliage density in a canopy layer,

$L_a =$ total one-sided foliage area in a canopy layer,

$L_v =$ unit volume of the canopy layer,

$G_a =$ unit ground area,

$h =$ height (thickness) of the canopy layer.

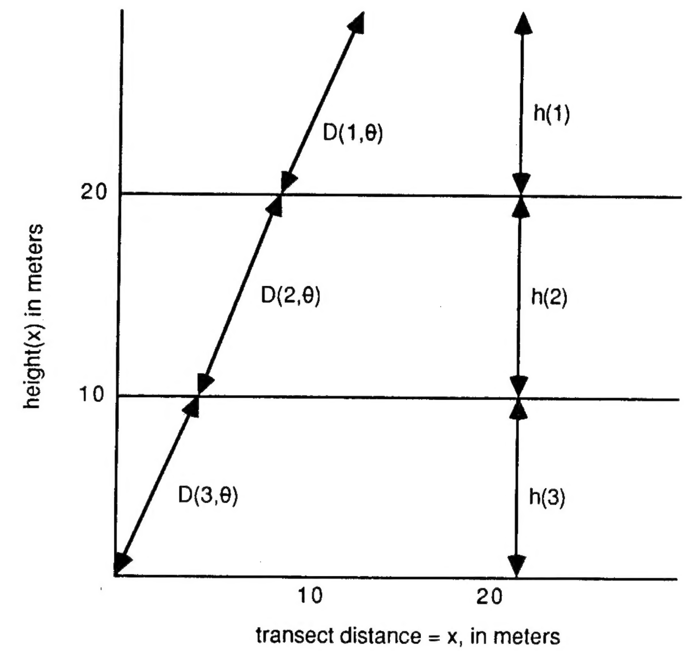
Assuming azimuthal independence, after substitution we have

$$P_{gap} = \exp[-K(\mathrm{LAI}/h)D(\theta)]. \qquad (6)$$

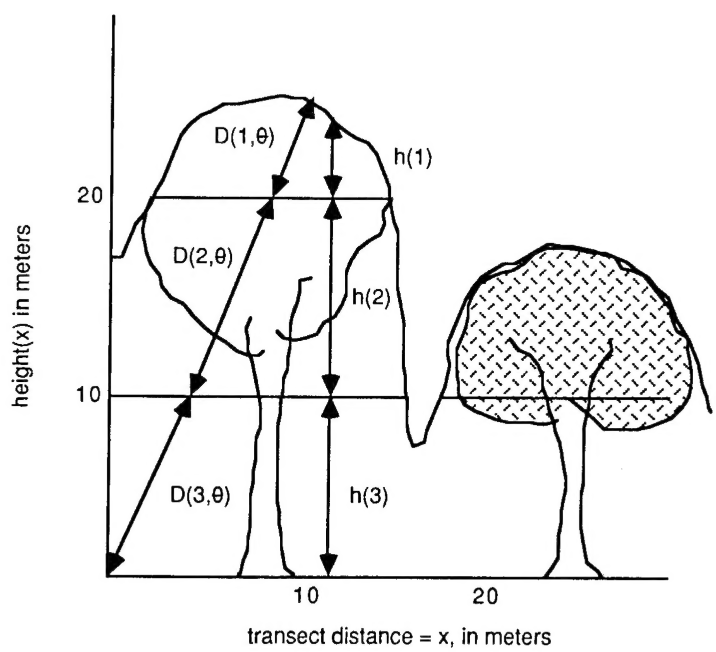
Once the foliage density is defined (i.e., LAI over some h) the various $D(\theta)$ can be computed for fixed points in the canopy. In our work, we use Fourier series expansions to describe measured or

abstract surface height functions. Figure 2 schematically illustrates the computation of $D(\theta)$ for a) a flat surface and b) an abstraction for a rough surface forest canopy.

Various techniques could be used to derive the surface height functions. The functions used in this study were derived from height transect data digitized from aerial photographs. The height transect data was then expanded in a Fourier series to develop the surface functions. A three-dimensional surface was not attempted at this time. Thus, to evaluate the rough surface modification to the thermal model, $D(\theta, \phi)$ was not computed, only $D(\theta)$.



(a) Flat surface



(b) Rough surface forest canopy abstraction

Figure 2. Illustration of $D(\theta)$ computation.

SITE DESCRIPTION

Experimental data were obtained at an existing research facility near Oak Ridge, Tennessee. The study site is located on the U.S. Department of Energy Oak Ridge Reservation west of the Oak Ridge National Laboratory's Walker Branch Watershed Research Facility. The site is used for ongoing forest meteorological and solar-radiation-interaction studies (Hutchison, 1982; Baldocchi et al., 1984; Balick and Hutchison, 1986) and was used for model validation in the previous thermal vegetation canopy model studies of Smith et al. (1981).

The forest at this site is representative of the Appalachian region and consists of an uneven-aged oak–hickory (*Quercus-Carya*) stand. The average height of the dominant trees is about 21.5 m, ranging from 17 to 26 m. The basal area is approximately 26 m^2/ha with an average diameter at breast height of 32 cm when last surveyed in 1976. The area is located on a ridge top at an elevation of 335 m above mean sea level. The soil at the site is a Fullerton cherty silt-loam (Typic Paleudult).

This facility has extensive instrumentation, including two 33 m triangular towers, a 44 m walkup tower, and a computerized data acquisition system. The two smaller towers are 35 m apart and are used to support an automated moving tram system instrumented with several radiometers at various levels. In addition, meteorological variables (i.e., air temperature, wind speed, humidity, etc.) are also recorded at different levels on the towers and are described later. The walkup tower provided access to the tram system and was used in this experiment to acquire radiance measurements within and above the forest canopy.

WITHIN CANOPY MEASUREMENTS

Both the ORIG and ROUGH model abstractions predict the average layer temperature for three canopy layers. Therefore, to evaluate the validity of the models, the forest canopy at the Walker Branch site was arbitrarily divided into three layers. The three canopy layers were chosen so that T1 represented the midpoint of the top layer, T2 the middle layer, and T3 the bottom layer. T1 was measured at 20 m, T2 at 13 m, and T3 at 6 m on the walk-up tower.

Two types of infrared thermometers (IRTs) were used to measure the canopy temperatures. One was an Everest Interscience Model 110, with a 3° field of view (FOV), and the other was a Raytek Raynger II Model R2LT,[1] with a 2° FOV. Both instruments measure radiant energy in the 8–12 μm range and temperature readings were taken by sweeping over a given area, thus yielding an area average rather than a point sample.

Four measurements were taken at each of the three levels by sweeping the hand-held IRT in the four cardinal directions. These four values were then averaged and this value was used as the average temperature for the midpoint of the layer. The entire sequence (T1,T2,T3) took about 5–10 min to record and was obtained bracketing the hour. Calibration checks of the IRT were made prior to each hourly acquisition. A complete set of data were acquired on two occasions, an overcast day, 22 August, 1984 (Day 235), from 0700 to 1700 EST, and a relatively clear day, 24 August, 1984 (Day 237), from 0700 to 1900 EST. The complete calibrated data obtained on the two days are given in Appendix A of McGuire (1986).

ABOVE CANOPY MEASUREMENTS

The models also predict canopy temperatures as a function of sensor view angle. To validate the models ability to predict view angle effects, several measurements were taken from above the forest canopy at different nadir view angles. One set of measurements was taken with a hand-held IRT and another set was obtained by an automated IRT.

Hand-Held IRT above Canopy

Measurements were taken of the top of the canopy at various viewing angles from the 35 m level of the walk-up tower. Here we assumed that the oak–hickory forest was homogeneous within the field of view of the IRTs as seen from the tower. The nadir angles chosen were 10°, 30°, 45°, 60°, and 85°, where 10° was looking down on the

[1]Reference to a company or product name does not imply approval or recommendation of the product to the exclusion of others that may be suitable.

canopy and 85° was off towards the horizon. A protractor with a plumb bob was taped to the hand-held instrument to estimate the angles to begin with and then was removed due to logistical problems. Pointing in each of the four cardinal directions, a sweep was made at each of the five nadir angles. Thus, each of the nadir angle temperature measurements represents an average value for the respective direction. More precise angular control would have been desirable, but estimating the angles and averaging the temperatures worked out best in terms of logistics and available equipment. These data were recorded bracketing the hour, with some half-hour measurements. The entire sequence (four azimuths, five nadir angles at each azimuth) took about 10–15 min. The data were recorded on a microcassette recorder and transferred to data sheets periodically.

Automated IRT above Canopy

In addition to the hand-held measurements, one Everest Model 110 was calibrated and mounted on a rotating shaft atop the walk-up tower. It was fixed at a 45° nadir angle and, as the shaft rotated, an automatic recording device recorded the canopy surface temperature at 20-s time intervals. This corresponds to about 12 azimuthal measurements for the fixed nadir angle every 3 min. Problems with the recording device led to an incomplete data set from the automated IRT. Partial data were obtained for the two measurement days (235 and 237) along with a complete set of data for the intermediate day. Although incomplete, these data help to verify the other IRT measurements and to illustrate trends in azimuthal variation of canopy temperatures.

MODEL INPUT PARAMETERS

Some of the input parameters required to drive the thermal model were taken from data previously collected at the Walker Branch site in the 1981 study. Previously digitized stereo aerial photography was used to obtain one-dimensional height transects through the canopy. The other canopy and environmental inputs are summarized below and given in Tables 1 and 2.

The leaf inclination angle distributions had been previously sampled throughout the canopy and were averaged over the appropriate layer-height intervals (see Hutchison et al., 1986). The LAI values used were 3.4, 0.8, and 0.4 for layers 1, 2, and 3, respectively. Short wave absorption coefficients, estimated by the SRVC model, were .089, .042, and .040 for the average mid-elements of the respective layers. Stomatal resistance was fixed at 0.07 min/cm for the daytime and infinity during nightime hours. Emissivity was set equal to 1.0 for all three canopy layers.

Table 1. Canopy Input Data for Oak–Hickory Forest (after Smith et al., 1981)

Inclination Angle \ *Foliage Angle Distribution (Probability of Occurrence)*	*Layer 1*	*Layer 2*	*Layer 3*
0	0.066	0.117	0.014
5	0.067	0.155	0.233
10	0.084	0.129	0.120
15	0.086	0.177	0.157
20	0.050	0.064	0.053
25	0.098	0.135	0.154
30	0.084	0.081	0.100
35	0.076	0.037	0.047
40	0.063	0.040	0.000
45	0.087	0.019	0.010
50	0.040	0.015	0.000
55	0.043	0.019	0.000
60	0.031	0.007	0.000
65	0.033	0.002	0.000
70	0.024	0.002	0.000
75	0.000	0.000	0.000
80	0.000	0.000	0.000
85	0.000	0.000	0.000
90	0.000	0.000	0.000
Leaf Area Index	3.40	0.80	0.40
Average shortwave absorption coefficients	0.089	0.042	0.040
Canopy density parameter	0.10	0.10	0.10

The environmental data were obtained from the automated recording system at the Walker Branch site. The environmental parameters required to drive the thermal model include:

T_a = air temperature, at 23 m (°C),

T_g = ground temperature, at 1 cm depth (°C),

WS = wind speed, at 44 m (m/s),

RH = relative humidity, at 44 m (%),

SWR = global shortwave radiation, at 44 m (W/m^2).

Table 2. Environmental Input Data for Oak–Hickory Forest

	Day 235 (22 August, 1984)					*Day 237 (24 August, 1984)*				
Time	T_a	T_g	*WS*	*RH*	*SWR*	T_a	T_g	*WS*	*RH*	*SWR*
100	21.0	21.1	0.842	.83	0.0	17.1	20.0	2.934	.60	0.0
200	21.0	21.0	0.939	.83	0.0	18.8	19.8	3.598	.59	0.0
300	20.3	21.0	0.735	.87	0.0	16.5	19.7	2.909	.63	0.0
400	20.2	20.9	0.750	.90	0.0	17.1	19.4	3.088	.65	0.0
500	19.5	20.7	1.192	.95	0.0	17.1	19.1	3.201	.69	0.0
600	19.3	20.7	2.374	.95	0.0	16.7	18.8	3.531	.72	0.0
700	19.9	20.6	2.006	.96	32.8	17.2	18.7	3.561	.73	66.4
800	20.9	20.7	1.389	.96	165.5	18.7	18.8	3.315	.74	248.9
900	22.2	20.8	2.092	.97	358.7	20.5	18.9	3.409	.74	456.2
1000	22.9	21.0	0.874	.88	299.3	21.7	19.1	3.114	.75	646.9
1100	24.3	21.4	1.060	.88	653.2	23.0	19.5	3.247	.69	788.0
1200	26.1	21.9	2.295	.80	783.0	24.6	20.0	2.892	.62	879.0
1300	26.9	22.2	1.501	.78	703.0	25.2	20.3	2.535	.56	831.0
1400	27.8	22.6	1.114	.78	687.7	25.9	20.7	2.249	.50	838.0
1500	28.2	22.8	1.639	.76	645.4	26.4	21.1	1.915	.51	740.0
1600	28.2	23.1	1.736	.72	385.0	26.0	21.3	2.164	.52	458.6
1700	27.3	22.9	1.650	.72	251.1	25.9	21.3	2.297	.52	399.8
1800	26.4	22.9	1.856	.76	123.5	23.6	21.3	2.396	.52	149.7
1900	25.5	22.7	1.868	.76	26.9	22.3	21.2	2.893	.55	34.0
2000	25.1	22.5	2.526	.76	0.0	21.3	20.9	3.042	.55	0.0
2100	22.5	22.3	3.353	.84	0.0	20.5	20.7	3.113	.56	0.0
2200	22.9	22.1	3.586	.84	0.0	20.1	20.5	3.725	.53	0.0
2300	22.2	22.0	3.971	.92	0.0	19.8	20.4	3.522	.53	0.0
2400	21.1	21.8	1.905	.94	0.0	19.4	20.2	4.148	.59	0.0

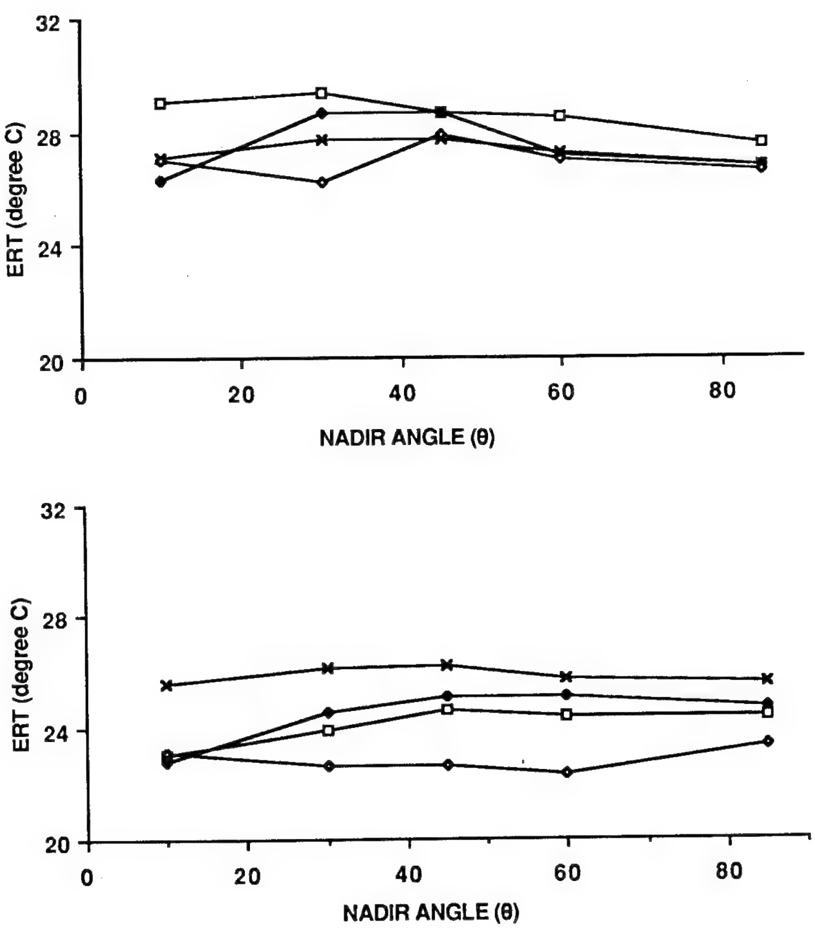


Figure 3. Day 237 hand-held IRT measurements. Top: (□) 1400 N; (◆) 1400 S; (×) 1400 E; (◇) 1400 W. Bottom: (□) 1600 N; (◆) 1600 S; (×) 1600 E; (◇) 1600 W.

WITHIN CANOPY COMPARISON —ORIG MODEL

Environmental data obtained on the two measurement days (235 and 237) were used to run the original thermal model over two 24-h periods. As expected, the layer temperatures followed the trend of the air temperatures throughout the two periods. Comparisons of the measured layer temperatures and the simulated effective radiant temperatures (ERTs) indicated there was good agreement. The largest deviation was 2°C, which occurred in Layer 1 on Day 237. Nighttime measurements were not made since previous results indicated a 1°C variation or less could be expected between predicted and measured temperatures, and the canopy would nearly equal the air temperature at night. The average deviation (absolute value) was less than 1°C for all layers on both measurement days.

ABOVE CANOPY COMPARISONS

Hand-Held IRTs—Four Cardinal Directions (Four Azimuths)

The overcast day (Day 235) revealed the expected isothermal response throughout the day, where the morning and evening (0700 and 1700 EST) angular measurements varied by less than 0.5°C between themselves and, at 1400 (about solar noon), the measurements varied between themselves by less than 1°C.

On Day 237, the relatively cloud-free day, the morning and evening measurements showed the same relatively isothermal response as was found on the overcast day. The measurements for these two time periods varied between themselves by less than 1.3°C for all azimuth and nadir angles. At solar noon (1400), the measurements were more variable than in the morning or evening, with a maximum variation of 3.2°C between the north and west 30° nadir angle measurements (Fig. 3).

In general, the measurements became more variable as the sun warmed the canopy, especially with respect to the azimuth angle. For example, at 1600, the maximum nadir variation is 2.3°, but the average nadir variation is generally less than 1.0°. On the other hand, the azimuthal variation at 1600, between the E and W measurements, is consistently different by an average of 3.1°, ranging from 2.5 to 4.0. These average values suggest that at certain times of the day, the azimuthal variations are more variable than the nadir variations. The nadir angle variations will be discussed in more detail in the section comparing the ORIG and ROUGH models. The azimuthal variations are also evident in the data from the automated IRT, which are discussed in the next section.

Automated IRT—Fixed Nadir, Variable Azimuth

As previously mentioned, a complete set of data was not obtained from the automated IRT fixed atop the tower; therefore, a rigorous comparison with other measurement data cannot be made. There was an overlap of data on Day 235 from 0700 to 1200, and the averages were compared with the within canopy (Layer 1) measurements and the hand-held measurements from above the canopy (average of the 45° view angle). There was good agreement between the three sensors, with an average deviation of 0.3°C and a maximum variation of 1.7°C. These results suggested to us that the auto-IRT data was providing reliable information.

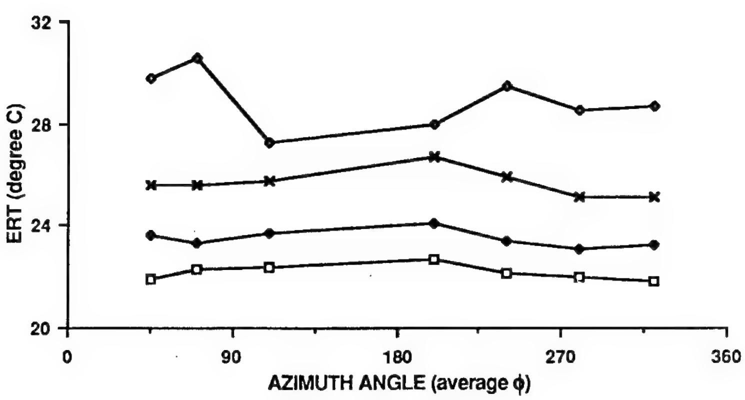


Figure 4. Day 235 auto-IRT measurements: (□) 0800; (◆) 1000; (×) 1100; (◇) 1200.

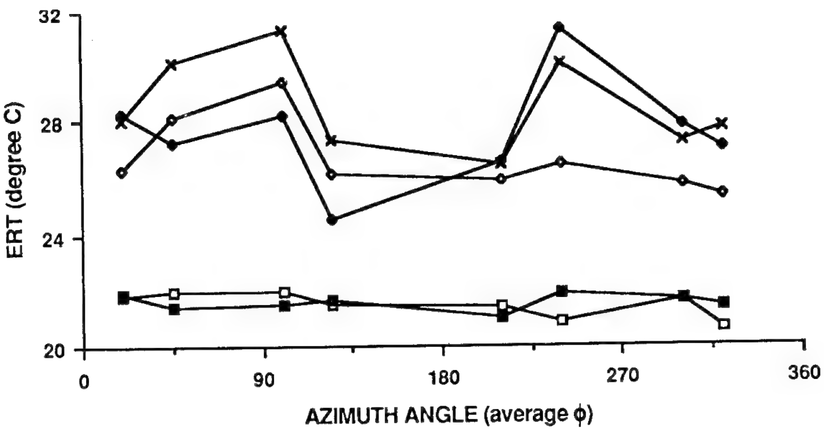


Figure 5. Day 236 auto-IRT measurements: (□) 0830; (◆) 1100; (×) 1400; (◇) 1600; (■) 1900.

Figures 4 and 5 illustrate the auto-IRT measurements for selected times on Days 235 and 236. For most of the morning on Day 235, the azimuthal variation was less than 0.5°C, with a maximum difference of 3.3° at 1200 between the azimuth angle measurements at 100 and 60. A complete set of auto-IRT data was available for Day 236, which was similar to Day 237, relatively clear with intermittent clouds. The morning and evening measurements (0830 and 1900) show the isothermal pattern generally expected, with differences less than 1.0°C.

The peaks in temperature variation on Day 236 tend to migrate throughout the day, probably in response to the sun's position, which results in shaded and unshaded sides of the rough canopy surface being measured. The most dramatic variation is seen at 1100 between the azimuth angles 240 (ERT = 31.3) and 125 (ERT = 24.5) with a difference of 6.8°C. Two maximums occur near solar noon (1400) at azimuth angles 100 and 240 with a difference from the 215 value of 4.9 and 3.6, respectively. By 1600 hours the major peak shifts to azimuth angle of 100 resulting in a maximum difference of 4.1° between the 100 and 340 temperatures. As evening approaches, the values return to an isothermal state (e.g., at 1900).

Although the auto-IRT data set was incomplete, it was useful in verifying the other sensors and in illustrating trends in azimuthal variation of canopy temperatures. The experimental data clearly show that the canopy temperatures may vary by 4–6° throughout the day. The other factor under investigation is the effect of the canopy surface on the response of the thermal sensor, which is discussed in the next section.

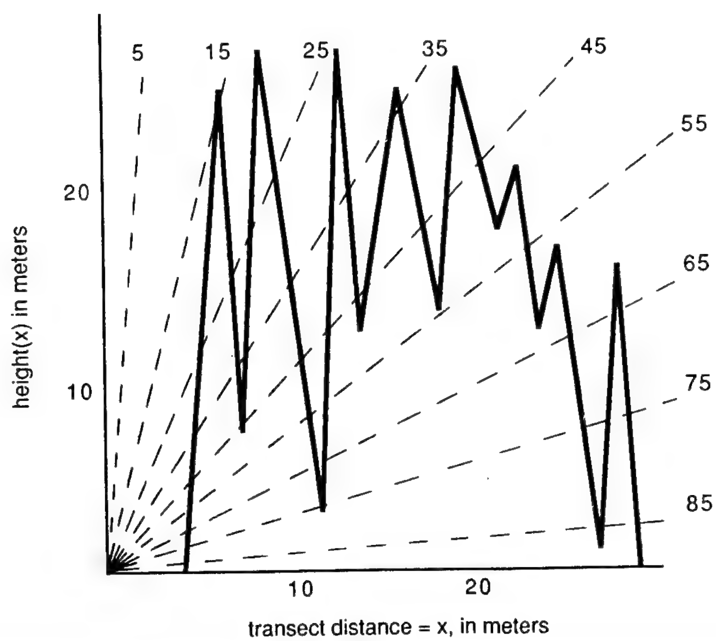


Figure 6. Height transect used to compute $D(\theta)$: (—) height profile; (– – –) nadir view angles.

Original and Rough Surface Models Compared

The environmental inputs for the two measurement days were used to drive the ORIG and ROUGH models. The thermal radiance predictions for the ROUGH model utilized a height profile described previously for computing $D(\theta)$. This profile was randomly selected as a typical height profile for this type of forest canopy (Fig. 6). Note the large gaps present at the near nadir angles (e.g., 5° and 15°). It was anticipated that this large gap would influence the P_{gap} expression and the resultant predicted temperatures at least at those nadir angles. Using this height profile, the canopy layer temperatures were compared first.

The predictions of the three canopy layer temperatures were essentially the same on both days using either model. Since both models predict the average layer temperature based on an average mid-element representative of that layer, they were expected to give very similar results, i.e., the "micro" geometric effects are the same. The view angle temperature prediction is where one would expect the "macro" geometric effects to have an influence.

Prior to comparing the models off-nadir predictions to the measurements, the following points must be made. First, the measurements, as stated earlier, represent averages for the various nadir angles. Secondly, both the ORIG and ROUGH models are assumed to be azimuthally independent and use average layer temperatures, coupled with the S and W matrices to compute the effects of the nadir view angles. Thus the ORIG model is based primarily on the "micro" effects, while the ROUGH model combines both the "micro" and the "macro" effects. Also, the height profile used in the ROUGH model, which was assumed to be representative of the forest, was for a specific transect through the forest. Therefore, the models do not exactly represent what was actually measured and most of the "micro" and "macro" effects have probably been averaged out of the measurements.

Since there is some question as to the exact representation of the measurements by the models, the average values of the measurements were compared to the model predictions. In the following plots, the average of the four cardinal directions was used for each nadir angle, thus intentionally averaging out any azimuthal variation, and perhaps some of the nadir variations. These average measurements were useful to verify the temperature predictions by the ORIG and ROUGH model, but not to verify the nadir angle predictions. The discussion will concentrate on the simulated nadir variations and use the average measurements for reference ERTs only.

Figures 7 and 8 show the ORIG model predictions, the ROUGH model predictions (R), and the average measured temperatures (M) as a function of nadir angle for selected times on Days 235 and 237, respectively. In all cases, the models matched the measurements to within 1.5°C at the 85° nadir angle. This error is on the same order as the within canopy comparisons discussed earlier (e.g., 1–2°C). This observation might be expected, since the "micro" and "macro" geometric effects would be minimized due to the large volume of canopy and increased distance being measured at these extreme nadir angles. In this sense, temperatures at large nadir angles may represent the average surface temperature, with the geometric effects removed.

Both models show trends in the nadir angle variations that are not present in the average of the measurements (for the averaging reasons previously discussed). Offnadir difference matrices (Kirchner et al., 1981) were computed from the thermal model outputs using the value at 5° as representing the nadir temperature, T(nadir), and

$$\text{OFFNADIR DIFFERENCE} = T(\theta) - T(\text{nadir}).$$

Both models predict the maximum offnadir variation just past solar noon (1400). The maximum difference is 1.6°C for the ORIG model, and 4.4°C for the ROUGH model for the same time period on Day 235 (see Fig. 7).

During the evening, the ORIG model predicts a maximum offnadir variation of -1.0°C, while the ROUGH model gives a maximum of -2.8°C, both at hour 300 on Day 237. The negative values implies that the extreme offnadir value (85°) is cooler than the value at nadir, contrasted with the opposite trend in the daytime. This may be explained in terms of the diurnal heating and cooling cycles of terrestrial features. During the day, the canopy surface is heated by the sun and shades the lower layers and soil background. In the evening, the reverse is true. The canopy begins to cool off, approaching air temperature, while the soil and lower layers retain the thermal energy longer. The lower layers will eventually cool down, and the soil will emit some of the stored thermal energy. At

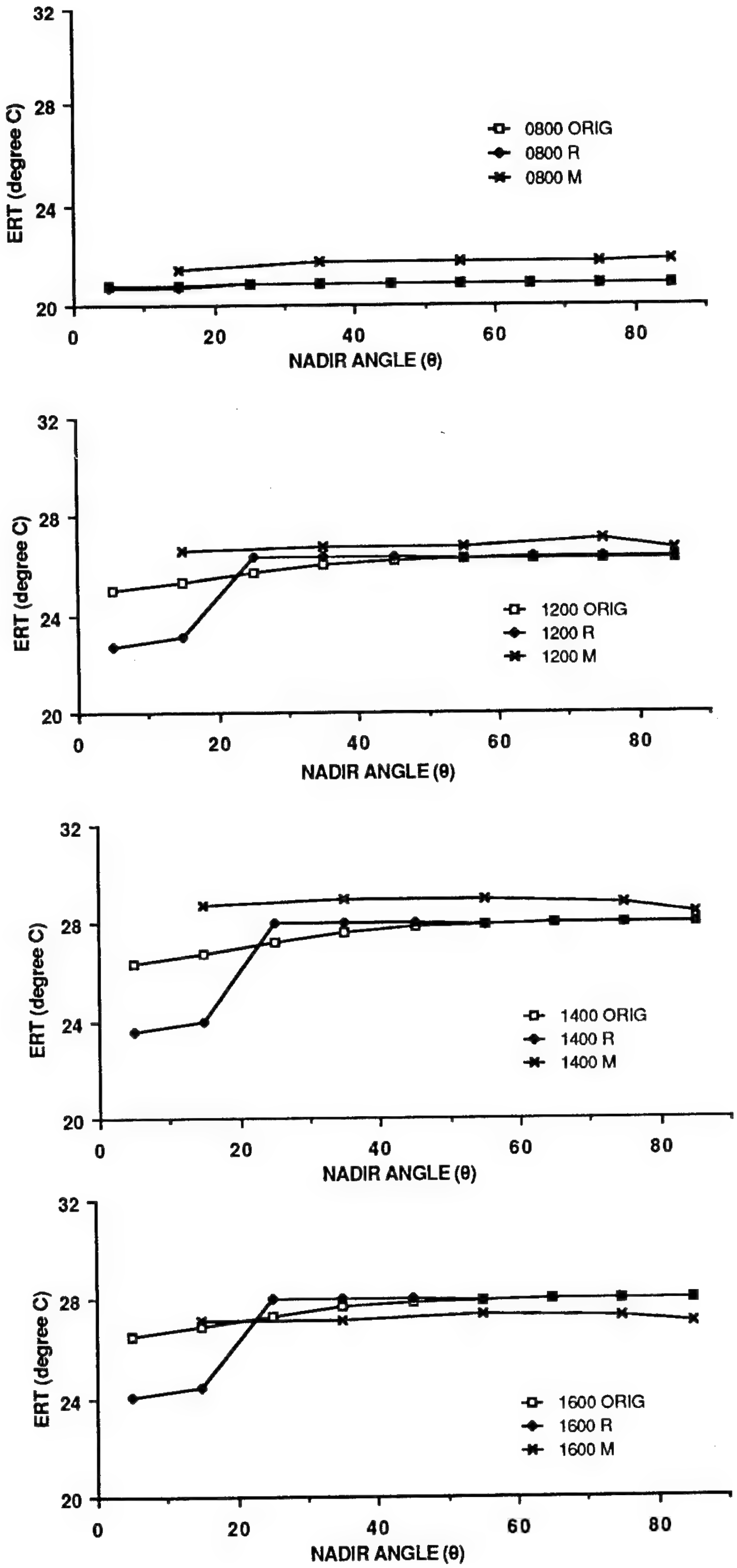


Figure 7. ORIG and ROUGH (R) model predictions and average measurements (M) for Day 235.

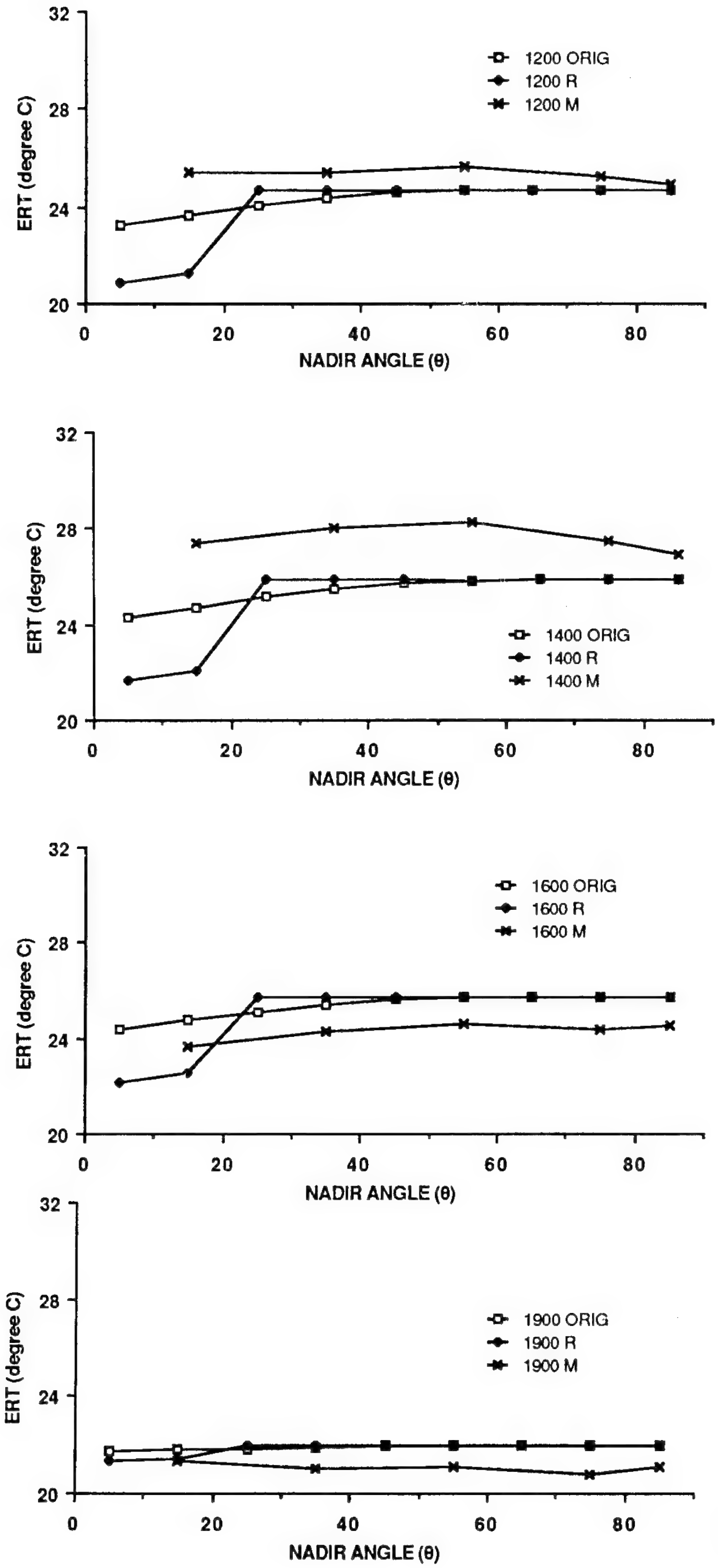


Figure 8. ORIG and ROUGH (R) model predictions and average measurements (M) for Day 237.

near nadir angles, the geometric structure and density of the canopy will determine how much the underlying layers will influence the recorded temperature. This effect is taken into account by both models, on the "micro" scale in the ORIG model and on both the "micro" and "macro" scales in the ROUGH.

Recall that the LAI for the top layer was 3.4, and 0.8 and 0.4 for the other two layers. Given this relatively dense top layer, and assuming a flat surface, the ORIG model does not show much nadir angle variation. However, given the height transect used in the ROUGH model runs (Fig. 6), the large gap present at the 5° and 15° angles seems to have an influence on the predicted temperature.

Notice that for all nadir angles and for both models, the offnadir predicted temperature reaches an asymptotic level near the 45° nadir angle. This implies that once the sensor "sees" so much canopy, the temperature tends to stabilize and approach the average surface temperature, independent of geometric effects (e.g., the 85° value discussed earlier). The high LAI for the top layer appears to dominate the off-angle effects, even with the large gap used in the ROUGH model.

CONCLUSIONS

A modification of a previously developed thermal vegetation canopy model has been presented, along with the measurements used to drive and verify the model. The evidence indicates that thermal radiance from a forest canopy depends on sensor viewing angle, solar position, and the degree of geometric roughness of the canopy surface. The original and modified models were first verified as to the prediction capabilities for the three average layer temperatures of the canopy. Simulations of the two models were very similar and it was felt that the modified model provided a prediction as accurate as the original model for the layer temperatures. The data analysis emphasized the view angle variations, both in the model comparisons and in the plots of the measurements.

The above canopy, hand-held IRTs were not useful for investigating the nadir angle variations due to the averaging technique used. These data did show some azimuthal variations, but it is difficult to precisely interpret the trends because of the averaging employed. The automated IRT was more useful in documenting the azimuthal variations. These data showed that canopy temperatures may vary by 4–6°, depending upon azimuth angle.

Comparisons were made between the ORIG and ROUGH thermal models. The ROUGH model utilized actual height profile data derived from digitized aerial photography. A transect was selected and the $D(\theta)$ values computed and input into the ROUGH model. The maximum off-nadir angle variation in the ORIG model was 1.6°C, compared with 4.4°C for the ROUGH model. The ROUGH model appeared to be sensitive to large gaps in the canopy profile, which influenced the predicted temperature. The ORIG model was influenced by the "micro" geometric effects only. Both models responded as would be expected, given the abstractions used. They reached an asymptotic temperature near the 45° nadir angle, which closely approximated the ERTs measured at that angle.

The data analysis and model comparisons suggest that thermal radiance from a forest canopy does depend on sensor view angle and that the variation can be partially explained by the position of the sun and the geometrically rough structure of the canopy surface. To help understand these variations, the following recommendations are made for further work:

1. There needs to be more precise angular control on the measurements taken. The model and measurements need to be "looking at" the same surface to make a more reasonable comparison and to further evaluate the actual variations present. An instrument such as the one described by Balick and Hutchison (1986) and Balick et al. (1987) would be useful. They utilized a rotating, seven-detector array suspended above the Walker Branch site in a leafless and fully leaved condition. The seven detectors were fixed at various nadir look angles and the entire array rotated to obtain complete view angle exitance distributions.
2. The height profile used in this study was only one of the many transects and methods that could have been used. It would be useful to run the ROUGH model with other transects and evaluate the canopy surface effects, combined with corresponding thermal imagery or

with some terrain profiling data (e.g., Nelson et al., 1984; Balick, 1987).

3. The analysis reported here suggests that the position of the sun and the geometrically rough canopy surface influences the angular variations in thermal exitance. Such effects may also be active in the short-wave energy absorption (i.e., sunlit and shaded regions) and could account for the combined effects of the sun and the rough canopy surface. The effect of using an average short-wave absorption coefficient on the predicted temperatures needs to be pursued. Future modeling efforts need to incorporate the full range of viewing angles, including azimuth angle prediction capabilities.
4. The sensitivity of the canopy ERTs to the spatial variations of the "micro" structure (i.e., LAI, foliage inclination angle distribution, foliage density, etc.) and nonfoliar components (i.e., woody biomass) needs to be examined further. Previous analyses indicates that canopy ERTs are sensitive to the LAI values (McGuire, 1986; Sader, 1986) and measured ERTs depend on the amount of woody biomass present in the instruments FOV (Balick and Hutchison, 1986). This has implications for future thermal remote sensing of such canopy parameters as biomass and for inputs to energy budget models.

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REFERENCES

Baldocchi, D. D., Matt, D. R., Hutchison, B. A., and McMillen, R. T. (1984), Solar radiation within an oak–hickory forest: An evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods, *Agric. Forest Meteorol.* 32:307–322.

Balick, L. K. (1987), A forest canopy height surface model for scene simulation, *Simulation* 49(1):5–12.

Balick, L. K., and Hutchison, B. A. (1986), Directional thermal infrared exitance distributions from a leafless deciduous forest, *IEEE Trans. Geosci. Remote Sens.* GE-24(5):693–698.

Balick, L. K., and Wilson, S. K. (1980), Appearance of irregular tree canopies in nighttime high-resolution thermal infrared imagery, *Remote Sens. Environ.* 10:299–305.

Balick, L. K., Scoggins, R. K., and Link, L. E., Jr. (1981), Inclusion of a simple vegetation layer in terrain temperature models for thermal infrared (IR) signature prediction, Misc. Paper EL-81-4, Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180.

Balick, L. K., Hutchison, B. A., Smith, J. A., and McGuire, M. J. (1987), Directional thermal infrared exitance distributions of a deciduous forest in summer, *IEEE Trans. Geosci. Remote Sens.* GE-25(3):410–412.

Bonn, F. J. (1977), Ground truth measurements for thermal infrared remote sensing, *Photogramm. Eng. Remote Sens.* 43(8):1001–1007.

Burden, R. L., Faires, J. D., and Reynolds, A. C. (1981), *Numerical Analysis*, 2nd ed., Prindle, Weber and Schmidt, Boston, MA.

Cheevasuvit, F., Taconet, O., and Vidal-Madjar, D. (1985), Thermal structure of an agricultural region as seen by NOAA-7 AVHRR, *Remote Sens. Environ.* 17:153–163.

Choudhury, B. J., and Idso, S. B. (1984), Simulating sunflower canopy temperatures to infer root-zone soil water potential, *Agric. Forest Meteorol.* 31:69–78.

Cooper, K. D., and Smith, J. A. (1985), A Monte Carlo reflectance model for soil surfaces with three dimensional structure, *IEEE Trans. Geosci. Remote Sens.* GE-23(5):668–673.

Deardoff, J. W. (1978), Efficient prediction of ground surface temperature with inclusion of a layer of vegetation, *J. Geophys. Res.* (83):1889–1904.

Dozier, J., and Warren, S. G. (1982), Effect of viewing angle on the brightness temperature of snow, *Water Resources Res.* 18(5):1424–1434.

Fritschen, L. J., Balick, L. K., and Smith, J. A. (1982), Interpretation of infrared nighttime imagery of a forested canopy, *J. Appl. Meteorol.* 21:730–734.

Gillespie, A. R., and Kahle, A. B. (1977), Construction and interpretation of a digital thermal inertia image, *Photogramm. Eng. Remote Sens.* 43(8):983–1000.

Goetz, A. F. H., Rock, B. N., and Rowan, L. C. (1983), Remote sensing for exploration: an overview, *Econ. Geol.* 78(4):573–590.

Hapke, B. (1984), Bidirectional reflectance spectroscopy—correction for macroscopic roughness, *Icarus* 59:41–49.

Hatfield, J. L. (1979), Canopy temperatures: the usefulness and reliability of remote measurements, *Agron. J.* 71:889–992.

Hatfield, J. L., Pinter, P. J., Jr., Chasseray, E., Ezra, C. E.,

Reginato, R. J., Idso, S. B., and Jackson, R. D. (1984), Effects of panicles on infrared thermometer measurements of canopy temperature in wheat, *Agric. Forest Meteorol.* 32:97–105.

Heilman, J. L., Kanemasu, E. T., Rosenberg, N. J., and Blad, B. L. (1976), Thermal scanner measurement of canopy temperatures to estimate evapotranspiration, *Remote Sens. Environ.* 5:137–145.

Heilman, J. L., Heilman, W. E., and Moore, D. G. (1981), Remote sensing of canopy temperature at incomplete cover, *Agron. J.* 73:403–406.

Hutchison, B. A. (1982), The atmospheric turbulence and diffusion laboratory forest meteorology research project: a review of forest meteorology research activities at Oak Ridge, ATDL Cont. File No. 40-A, ATDL, Oak Ridge, TN 37830.

Hutchison, B. A., Matt, D. R., McMillen, R. T., Gross, L. J., Tajchman, S. J., and Norman, J. M. (1986), The architecture of a deciduous forest canopy in eastern Tennessee, USA, *J. Ecol.* 74:635–676.

Jackson, R. D., Reginato, R. J., Pinter, P. J., Jr., and Idso, S. B. (1979), Plant canopy information extraction from composite scene reflectance of row crops, *Appl. Opt.* 18(2): 3775–3782.

Kahle, A. B., and Goetz, A. F. H. (1983), Mineralogic information from a new airborne thermal infrared multispectral scanner, *Science* 222:24–27.

Kimes, D. S. (1979), A thermal vegetation canopy model of sensor responses, Ph.D. dissertation, Colorado State University, Fort Collins, CO 80523.

Kimes, D. S. (1980), Effects of vegetation canopy structure on remotely sensed canopy temperatures, *Remote Sens. Environ.* 10:165–174.

Kimes, D. S. (1981a), Azimuthal radiometric temperature measurements of wheat canopies, *Appl. Opt.* 20(7): 1119–1121.

Kimes, D. S. (1981b), Remote sensing of temperature profiles in vegetation canopies using multiple view angle and inversion techniques, *IEEE Trans. Geosci. Remote Sens.* GE-19(2):85–90.

Kimes, D. S. (1983), Remote sensing of row crop structure and component temperatures using directional radiometric temperatures and inversion techniques, *Remote Sens. Environ.* 13:33–55.

Kimes, D. S., and Smith, J. A. (1980), Simulation of solar radiation absorption in vegetation canopies, *Appl. Opt.* 19:2801–2811.

Kimes, D. S., and Kirchner, J. A. (1982), Radiative transfer model for heterogeneous 3-D scenes, *Appl. Opt.* 21: 4119–4129.

Kimes, D. S., Idso, S. B., Pinter, P. J., Jr., Reginato, R. J., and Jackson, R. D. (1980), View angle effects in the radiometric measurement of plant canopy temperatures, *Remote Sens. Environ.* 10:273–284.

Kimes, D. S., Smith, J. A., and Link, L. E. (1981), A thermal IR exitance model of a plant canopy, *Appl. Opt.* 20(4):623–632.

Kirchner, J. A., Schnetzler, C. C., and Smith, J. A. (1981), Simulated directional radiances of vegetation from satellite platforms, *Int. J. Remote Sens.* 2(3):253–264.

Li, X., and Strahler, A. H. (1985), Geometric-optical modeling of a conifer forest canopy, *IEEE Trans Geosci. Remote Sens.* GE-23(5):705–721.

Li, X., and Strahler, A. H. (1988), Modeling the gap probability of a discontinuous vegetation canopy, *IEEE Trans. Geosci. Remote Sens.* GE-25(2):161–170.

Mahrer, Y. (1982), A theoretical study of the effect of soil surface shape upon the soil temperature profile, *Soil Sci.* 134(6):381–387.

McGuire, M. J. (1986), Directional thermal properties of a forest canopy, Ph.D. dissertation, Colorado State University, Fort Collins, CO 80523.

Millard, J. P., Jackson, R. D., Goettelman, R. C., Reginato, R. J., and Idso, S. B. (1978), Crop water-stress assessment using an airborne thermal scanner, *Photogramm. Eng. Remote Sens.* 44(1):77–85.

Nelson, R., Krabill, W., and MacLean, G. (1984), Determining forest canopy characteristics using airborne laser data, *Remote Sens. Environ.* 15:201–212.

Nilson, T. (1970), A theoretical analysis of the frequency of gaps in plant stands, *Agric. Meteorol.* 7:25–38.

Norman, J. M., and Welles, J. M. (1983), Radiative transfer in an array of canopies, *Agron. J.* 75:481–488.

Otterman, J. (1984), Albedo of a forest modeled as a plane with dense protrusions, *J. Climate Appl. Meteorol.* 23:297–307.

Pierce, L. L., and Congalton, R. G. (1988), A methodology for mapping forest latent heat flux densities using remote sensing, *Remote Sens. Environ.* 24:405–418.

Price, J. C. (1981), The contribution of thermal data in Landsat multispectral classification, *Photogramm. Eng. Remote Sens.* 47(2):229–236.

Price, J. C. (1982), Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data, *IEEE Trans. Geosci. Remote Sens.* GE-20(3):286–292.

Rhode, W.G., and Olson, C. E., Jr. (1970), Detecting tree moisture stress, *Photogramm. Eng. Remote Sens.* 36(6): 561–566.

Sabins, F. F., Jr. (1973), Flight planning and navigation for thermal-IR surveys, *Photogramm. Eng.* 39:49–58.

Sader, S. A. (1986), Analysis of effective radiant temperatures in a Pacific Northwest forest using Thermal Infrared Multispectral Scanner data, *Remote Sens. Environ.* 19:105–115.

Slater, P. N. (1985), Survey of multispectral imaging systems for earth observations, *Remote Sens. Environ.* 17:85–102.

Smith, J. A. (1983), Matter-energy interactions in the optical region, in *Manual of Remote Sensing*, 2nd ed. (R. N.

Colwell, ed.), American Society of Photogramm. and Remote Sens., Falls Church, VA 22046, Vol. 1.

Smith, J. A., Ranson, K. J., Nguyen, D., Balick, L., Link, L. E., Fritschen, L., and Hutchison, B. A. (1981), Thermal vegetation canopy model studies, *Remote Sens. Environ.* 11:311–326.

Soer, G. J. R. (1980), Estimation of regional evapotranspiration and soil moisture conditions using remotely sensed crop surface temperatures, *Remote Sens. Environ.* 9:27–45.

Strahler, A. H., Woodcock, C., Li, X., and Jupp, D. L. B. (1984), Discrete object modeling of remotely sensed scenes, *Proc. Eighteenth Int. Sym. Remote Sensing of Environment*, Paris, France.

Sutherland, R. A., and Bartholic, J. F. (1977), Significance of vegetation in interpreting thermal radiation from a terrestrial surface, *J. Appl. Meteorol.* 16(8):759–763.

Ulaby, F. T., Moore, R. K., and Fung, A. K. (1982), Radar remote sensing and surface scattering and emission theory, in *Microwave Remote Sensing, Active and Passive*, Addison-Wesley, Reading, MA, Vol. 2.

Weiss, R. A. (1982), Terrain mesoroughness description and its application to mobility and cover, in *Trans. of 28th Conf. of Army Mathematicians*, ARO Report 83-1, West Point, NY.

Weiss, R. A. (1984), Infrared modeling of terrain backgrounds, Army Science Conference, U.S. Army Waterways Experiment Station, Vicksburg, MS 39180.

Welles, J. M., Norman J. M., and Martsolf, J. D. (1979), An orchard foliage temperature model, *J. Am. Soc. Hortic. Sci.* 104(5):602–610.

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13. ABSTRACT (*Maximum 200 words*)

This paper describes an extension of an existing thermal vegetation canopy radiance model which has been modified to partially account for the geometrically rough structure of a forest canopy. Fourier series expansion of a canopy height profile is used to calculate view factors which partially account for the directional variations in canopy thermal radiance transfer.
A modification of a previously developed thermal vegetation canopy model is presented, along with the measurements used to drive and verify the model. The evidence indicates that thermal radiance from a forest canopy depends on sensor viewing angle, solar position, and the degree of geometric roughness of the canopy surface. For the above canopy, hand-held IRT's were not useful for investigating the nadir angle variations due to the averaging technique used. These data did show some azimuthal variations, but it is difficult to precisely interpret the trends because of the averaging employed. Comparisons were made between the ORIG and ROUGH thermal models. The data analysis and model comparisons suggest that thermal radiance from a forest canopy does depend on sensor view angle and that the variation can be partially explained by the position of the sun and the geometrically rough structure of the canopy surface.

14. SUBJECT TERMS
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